



Guidelines for Head Tactile Communication

by Kimberly Myles and Joel T. Kalb

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March 2010

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Aberdeen Proving Ground, MD 21005-5425

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14. ABSTRACT A helmet-mounted tactile display is desired for military applications such as cueing to alert Soldiers to the direction and location of an event or indicating movement direction in GPS-supported navigation. However, the system must be compatible with the head sensitivity of the user to ensure the user's optimal perception of the provided information. The purpose of this report is to document the overall findings of the basic research program regarding head tactile sensitivity and to provide answers to two basic questions: (1) What locations on the head are most sensitive to vibration stimulation? (2) What is the optimal frequency for tactile signals to be applied to the head? The overall findings are discussed and are considered as initial guidelines for head tactile communication and for using vibration stimulation on the head.					
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1. Introduction

A few years ago, the authors were tasked to answer the question, Can the head be used as a communication tool for providing tactile alerts to the Soldier in hopes of alleviating sensory overload on the Soldier's visual and auditory channels? To answer the question, the authors initially intended to design a prototype head-mounted tactile display (HMTD) to test Soldier performance. While searching for the best parameters to build the HMTD, the authors discovered that very little research had been done on head tactile stimulation. The lack of research regarding head tactile sensitivity and stimulation produced minimal background data from which to design a head device.

For example, current research regarding basic tactile sensitivity measures or applicable equipment design solutions that utilize the tactile modality is largely dedicated to the finger (Morioka et al., 2008; Rabinowitz et al., 1987; Stuart et al., 2003; Wilska, 1954), hand (Verrillo, 1962), arm/forearm (Cholewiak and Collins, 2003; Morioka et al., 2008; Piateski and Jones, 2005; Stuart et al., 2003; Verrillo, 1966; Wilska, 1954), torso (Piateski and Jones, 2005; Van Erp, 2005; Van Erp and Werkhoven, 1999; Wilska, 1954), wrist (Ferris and Sarter, 2008), shoulder (Stuart et al., 2003; Wilska, 1954), cheek (Stuart et al., 2003), thigh/chin/forehead (Wilska, 1954), foot (Morioka et al., 2008; Nurse and Nigg, 1999), and toe (Morioka et al., 2008; Wilska, 1954). The list clearly shows a gap in the body of research regarding tactile sensitivity measures for the head.

An HMTD is envisioned for use with military applications such as alerting Soldiers to the direction and location of an event or indicating movement direction in GPS-supported navigation. However, the system must be compatible with the head sensitivity of the user to ensure the user's optimal perception of the information transmitted. The purpose of the experiment was to evaluate the effect of background noise on vibration thresholds for the head. The authors wanted to know if background noise (i.e., noise on the battlefield) would affect the Soldier's ability to detect tactile signals on the head. The purpose of this report was to determine head tactile sensitivity for the basic research program and to provide answers to two basic questions (Myles and Binseel, 2007, 2009): (1) What locations on the head are most sensitive to vibration stimulation? (2) What is the optimal frequency for tactile signals that will be applied to the head? The overall findings are discussed and are considered as initial guidelines for head tactile communication and using vibration stimulation on the head.

2. Experiment 1

The purpose of experiment 1 was to obtain vibration thresholds for the head (seven head locations) and evaluate if thresholds differed as a function of head location, frequency, and background noise.

2.1 Method

2.1.1 Participants

Twenty-two U.S. Marines (all males) were recruited for this study, and a portable audiometer (Maico AC-40) was used to conduct hearing screenings to ensure that each participant's hearing threshold was in the normal range. The screenings were conducted at a 20-dB hearing level (HL) at octave audiometric frequencies between 250 and 4000 Hz by presentation of tones through supra-aural headphones. The mean age of participants was 20 years ($SD = 1.74$), with a range of 18 to 24 years. Previously reported data from Myles and Kalb (2009), consisting of 11 participants, was used for the quiet noise condition in this experiment.

2.1.2 Apparatus and Stimuli

The C-2 Tactor designed by Engineering Acoustics, Inc. (www.eaiinfo.com) was used for this study. The C-2 Tactor is 1.2 in (diameter) \times 0.31 in (height) and weighs 17 g. Its moving contactor surface is 0.3 inch in diameter.

A computer-generated, modulated sinusoidal carrier wave with a 10-V peak amplitude was used as the vibration stimulus. Each stimulus contained a cycle period of 250 ms, a duty cycle fraction of 0.25, and three repetitions extending the stimulation period of the signal to 750 ms (figure 1). Furthermore, the signal was divided into three equal phases during the on time of the duty cycle—namely, the rise, sustain, and fall. Rise and fall both followed a half cosine response while sustain was at full modulation. Each signal was attenuated, sent to one of seven multiplexer channels, and amplified by a unity-voltage-gain power driver that was connected to a tactor (figure 2).

The noises used in this experiment consisted of pink and High-Mobility Multipurpose Wheeled Vehicle (HMMWV) (25 mph at the driver's ear) recordings that were played through four, 8-ohm Bose surface mount speakers placed around the perimeter of the testing station. They were played at a level of 85 dB(A) as measured at the listener location. Pink noise represented uniform masking of the listener's critical band of hearing, and HMMWV noise represented a real-world noise that Soldiers are likely to encounter on the battlefield. The sounds were stored on a computer and sent to multiplexed power amplifiers.

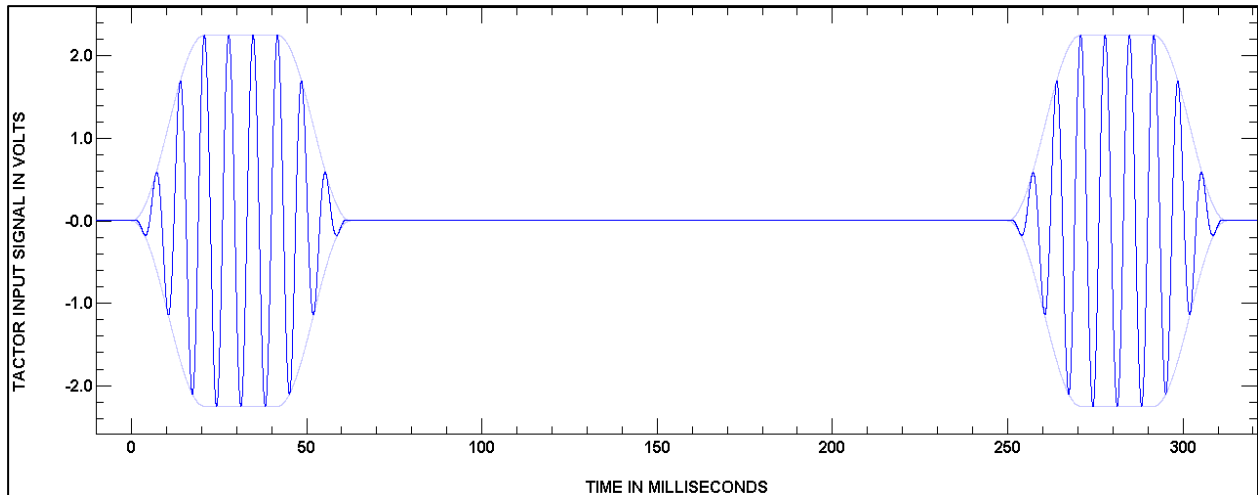


Figure 1. Diagram of the signal.

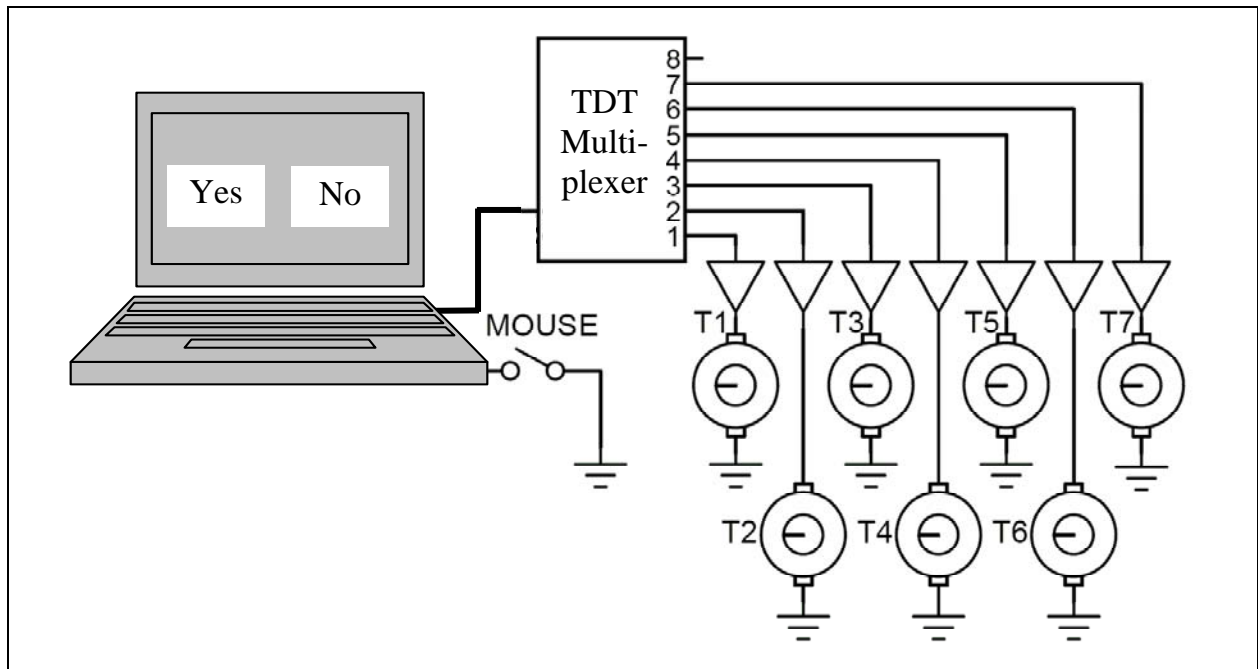


Figure 2. Diagram of equipment showing Tucker-Davis Technologies System II and the seven tactors.

2.1.3 Procedure

Participants were seated in a standard office chair in an Industrial Acoustics Company sound-attenuating chamber and provided a consent form to review and sign if they agreed to participate. The seven head locations chosen for this experiment follow the 10-20 system of electrode placement used for high-density electroencephalography (EEG) studies (figure 3).

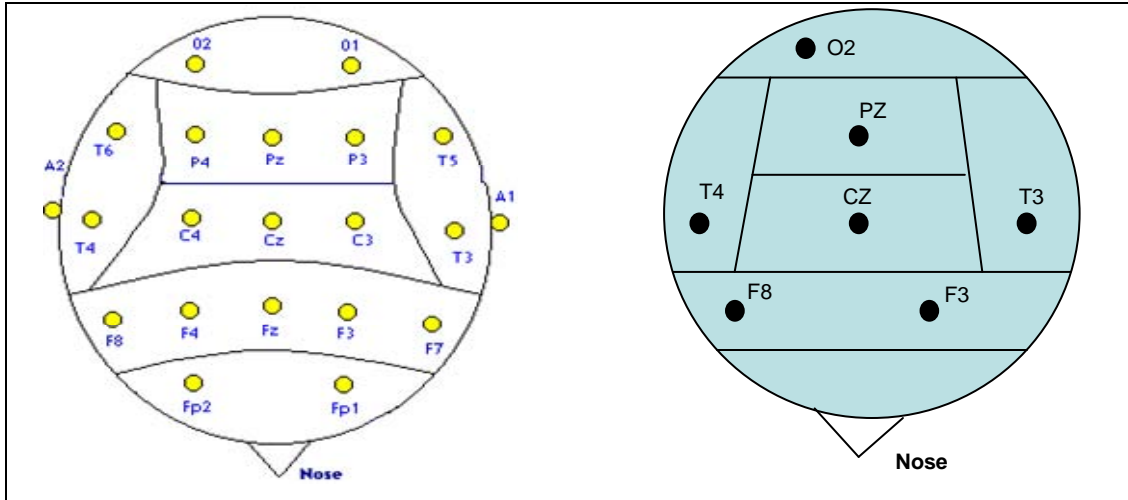


Figure 3. A 10-20 system of electrode placement (adapted from D. G. Domenick [2006]) and the seven locations chosen for experiment 1.

Therefore, seven tactors were placed in a headband designed to hold one tactor at each chosen head location. The experimenter placed the stretchable headband on the participant's head (secured with Velcro fasteners), examined the headband to ensure that all tactors made proper contact with the scalp, and measured the static force (using a Digital Force Gauge) created by the tension of the headband.

Vibration threshold measurements were obtained using the psychophysical adaptive procedure ZEST (Zippy Estimation by Sequential Testing). For an in-depth review regarding how this procedure was used to obtain threshold measurements, see Myles and Kalb (2009).

Each participant was assigned to either the pink or HMMWV noise condition.* The appropriate background noise was turned on and measured at 85 dB(A) using a sound level meter. Each head location was tested one at a time, and the presentation order of head location was randomized. The presentation order of frequency (32, 45, and 63 Hz) within head location was also randomized. Each treatment was presented 10 times for a total of 210 vibration stimuli presented to the head of each participant. The last response obtained on trial 10 was recorded as the vibration threshold for that treatment within ± 1 dB error.

For each stimulus, participants used a mouse to click a YES button if they felt a vibrating sensation and a NO button if they did not feel a vibrating sensation. Prior to starting the experiment, the experimenter verified that each tactor was emitting a vibration stimulus, which also served as practice trials to familiarize the participants with the task and stimuli. Verification consisted of the experimenter identifying each tactor individually, sending a vibration stimulus to the identified location, and asking the participant to report if the stimulus was felt.

*Data from Myles and Kalb (2009) was used for the quiet condition in this experiment.

2.2 Results

A $3 \times 7 \times 3$ mixed design was used to determine the effect of noise condition (quiet, pink, HMMWV), head location (F8, F3, T4, CZ, T3, PZ, O2), and frequency (32, 45, and 63 Hz) on vibration threshold. Noise was used as a between-subjects variable, and head location and frequency were within-subjects variables. Vibration thresholds were measured as the skin displacement level required for the perception of a vibration stimulus. An analysis of variance (ANOVA) was used to compare the differences in thresholds attributable to head location, frequency, and noise condition, and significant effects were explored using least significant difference (LSD). The mean static force created on the head by the headband was 0.47 N. Due to potential confounds for the noise condition variable resulting from the combination of two different experiments, interpretations involving the variable were done with care.

An ANOVA revealed a significant main effect for head location, $F(6, 180) = 12.07, p < 0.01$, and a significant noise condition \times frequency interaction, $F(4, 60) = 4.48, p < 0.01$. The main effects of noise condition, $F(2, 30) = 0.32, p = 0.73$, and frequency, $F(2, 60) = 2.33, p = 0.11$, were not significant. In figure 4, head locations are arranged from least to most sensitive. Post hoc comparisons of the seven head locations revealed that vibration thresholds for T4, O2, PZ, and T3 were not significantly different. Also, thresholds for head locations CZ, F3, and F8 were not significantly different. However, head locations T4, O2, PZ, and T3 were significantly more sensitive ($p < 0.01$) to vibration stimulation than locations CZ, F3, and F8. To further evaluate the noise condition \times frequency interaction (figure 5), the frequency data were collapsed across head location at each level of noise, and for each level of noise, comparisons were performed between each possible pair of frequency levels. A paired sample t-test revealed that vibration thresholds in quiet were lower at 32 Hz than at 45 [$t(10) = 2.24; p = 0.05$] and 63 Hz [$t(10) = 2.60; p = < 0.05$].

2.2.1 Tactile Sensitivity by Head Region

A relative comparison of the head locations provides little information for the design of a head tactile display, so the data were organized into five head regions: central (CZ), frontal (F3, F8), temple (T3, T4), occipital (O2), and parietal (PZ). Head location data were collapsed across frequency and noise condition. A repeated measures one-way ANOVA was used to evaluate vibration thresholds by head region, and the analysis revealed a significant main effect for head region, $F(4, 128) = 16.31, p < 0.01$.

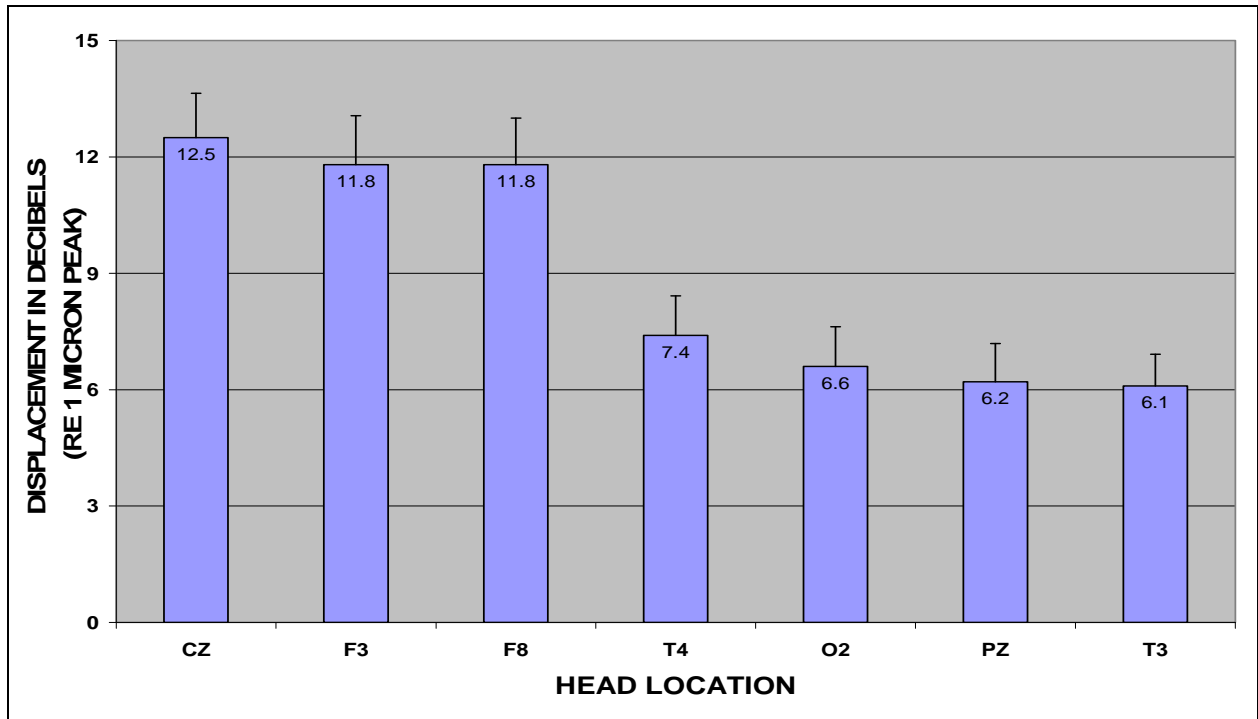


Figure 4. Mean displacement by head location for experiment 1. (The error bars indicate standard errors.)

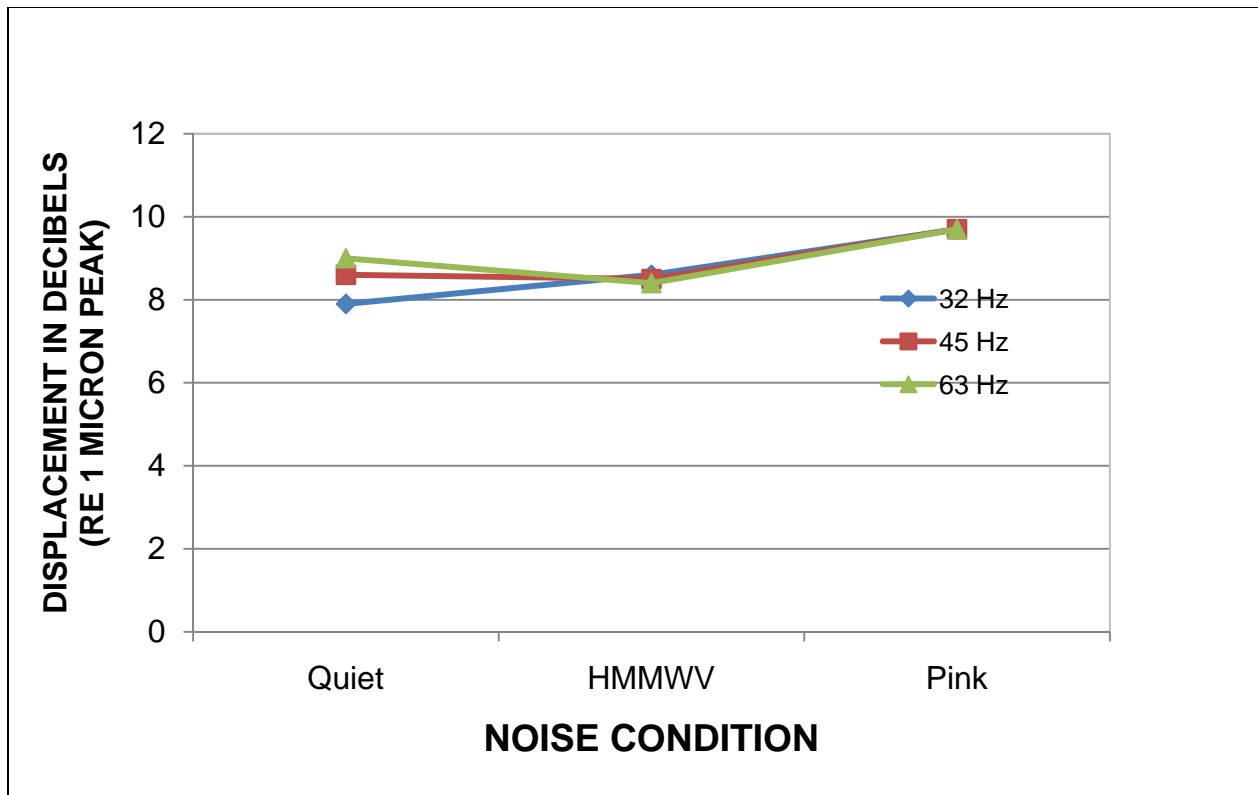


Figure 5. Noise condition by frequency interaction for experiment 1.

In figure 6, the head regions are arranged from least to most sensitive to vibration stimulation, and post hoc comparisons of the five head regions revealed that the central and frontal regions of the head were least sensitive to vibration while the parietal, occipital, and temple regions of the head were most sensitive to vibration. All comparisons were significant at $p < 0.01$.

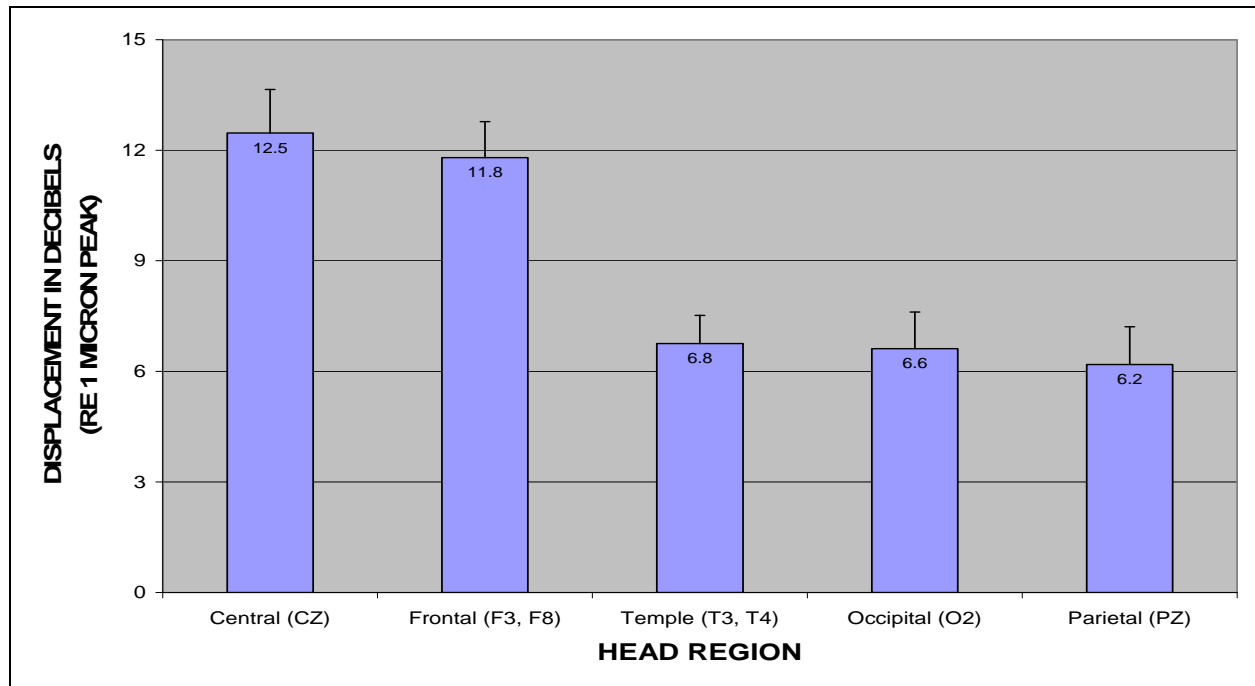


Figure 6. Mean displacement by head region for experiment 1. (The error bars indicate standard errors.)

3. Experiment 2

The purpose of experiment 2 was to obtain vibration thresholds for the head (eight additional head locations) and evaluate if thresholds differed as a function of head location, frequency, and background noise.

3.1 Method

3.1.1 Participants

Thirty-three Marines (32 males, 1 female) were recruited for this study, and a portable audiometer (Maico AC-40) was used to conduct hearing screenings to ensure that each participant's hearing threshold was in the normal range of hearing. The screenings were conducted at a 20-dB HL at octave audiometric frequencies between 250 and 4000 Hz by presentation of tones through supra-aural headphones. The mean age of participants was 20 years ($SD = 2.95$), with a range of 18 to 30 years.

3.1.2 Apparatus and Stimuli

The apparatus and stimuli used in this experiment were the same as used in experiment 1.

3.1.3 Procedure

The procedures were the same as in experiment 1, except vibration threshold measurements were obtained for eight different head locations (figure 7), participants were assigned to either the quiet, pink, or HMMWV noise level, and participants received a total of 240 vibration stimuli.

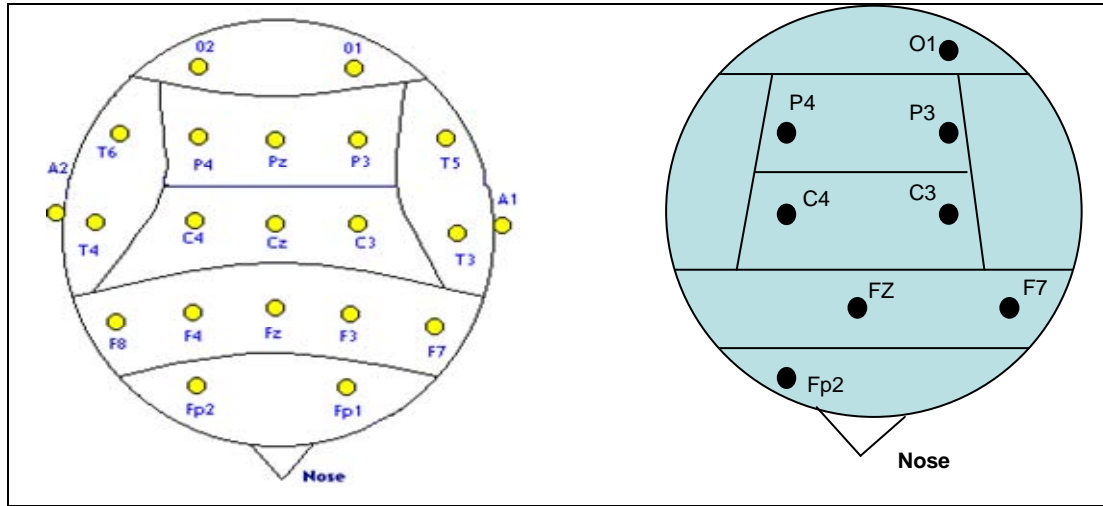


Figure 7. A 10-20 system of electrode placement (adapted from D. G. Domenick [2006]) and the eight locations chosen for experiment 2.

3.2 Results

A $3 \times 8 \times 3$ mixed design was used to determine the effect of noise condition (quiet, pink, HMMWV), head location (Fp2, FZ, F7, C4, C3, P4, P3, O1), and frequency (32, 45, and 63 Hz) on vibration threshold. Noise was used as a between-subjects variable, and head location and frequency were within-subjects variables. An ANOVA was used to compare the differences in thresholds attributable to head location, frequency, and noise condition, and significant effects were explored using LSD. The mean static force created on the head by the headband was 0.55 N.

An ANOVA revealed a significant main effect for head location, $F(7, 210) = 3.10, p < 0.01$, and a significant noise condition \times frequency interaction, $F(4, 60) = 3.30, p < 0.05$. The main effect of noise condition, $F(2, 30) = 1.22, p = 0.31$, was not significant, but frequency, $F(2, 60) = 3.12, p = 0.051$, did approach significance. In figure 8, head locations are arranged from least to most sensitive. Post hoc comparisons revealed that head location Fp2 was significantly more sensitive to vibration stimulation than locations P4 and C3, $p < 0.01$. The remaining comparisons revealed that head location P4 was also significantly less sensitive to vibration than

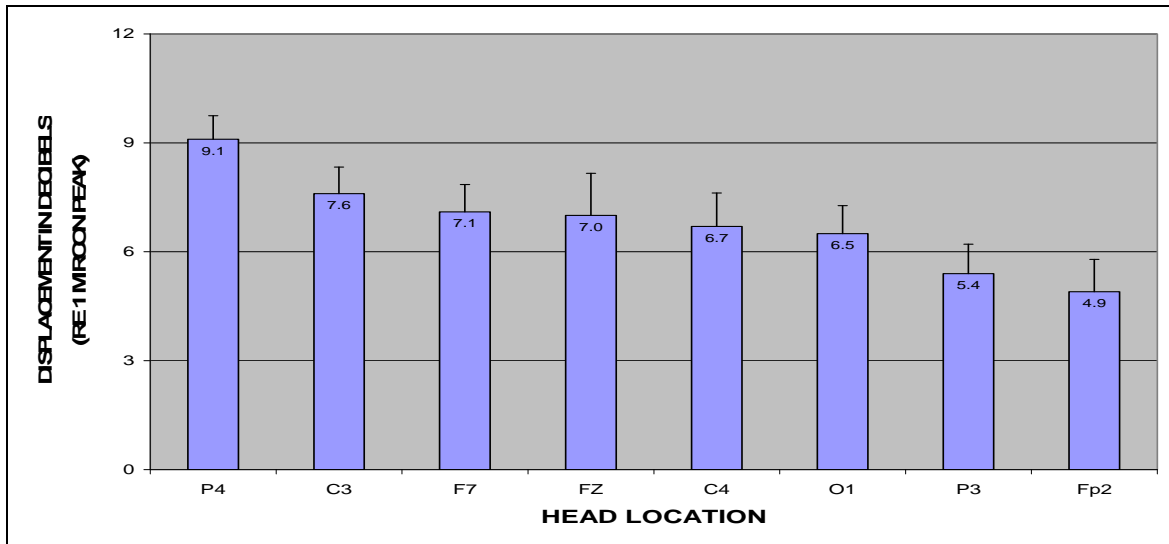


Figure 8. Mean displacement by head location for experiment 2. (The error bars indicate standard errors.)

locations C4, O1, and P3, $p < 0.01$. Head location FZ was neutral and was not significantly different from any of the other head locations, and head locations C4, O1, P3, and Fp2 were not significantly different from one another. The frequency approached significance, which strongly suggested that vibration thresholds may be lower at 32 Hz than at 45 or 63 Hz, $p = 0.04$ (figure 9). To further evaluate the noise condition \times frequency interaction (figure 10), the frequency data were collapsed across head location at each level of noise, and for each level of noise, comparisons were performed between each possible pair of frequency levels. A paired sample t-test revealed that vibration thresholds in the pink noise condition were significantly lower at 32 Hz than at 45 Hz, $t(10) = 3.28$, $p < 0.01$.

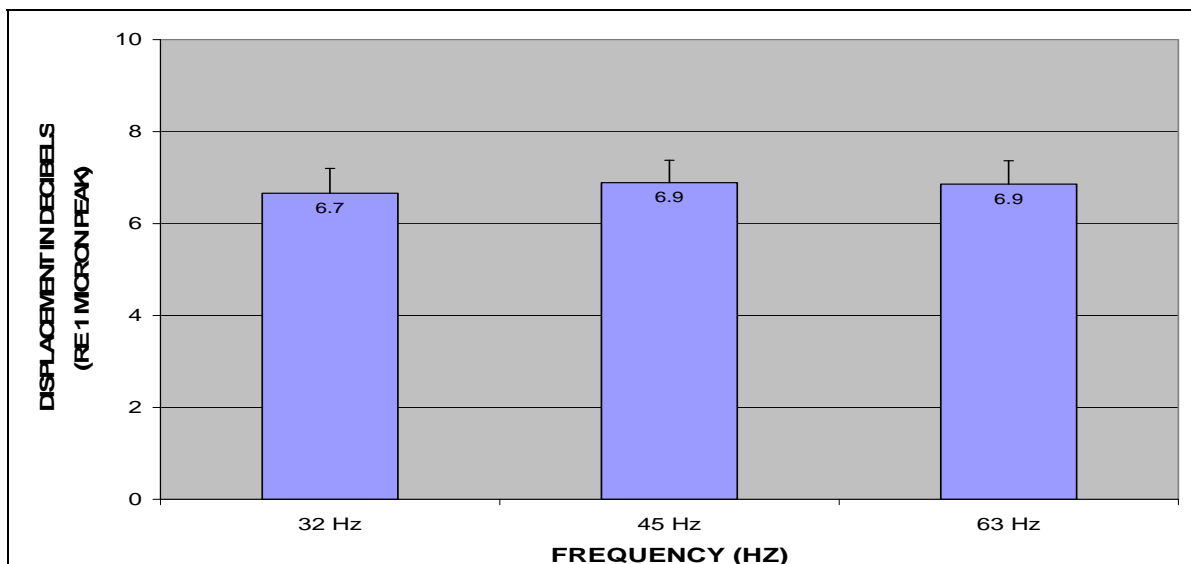


Figure 9. Mean displacement by frequency for experiment 2. (The error bars indicate standard errors.)

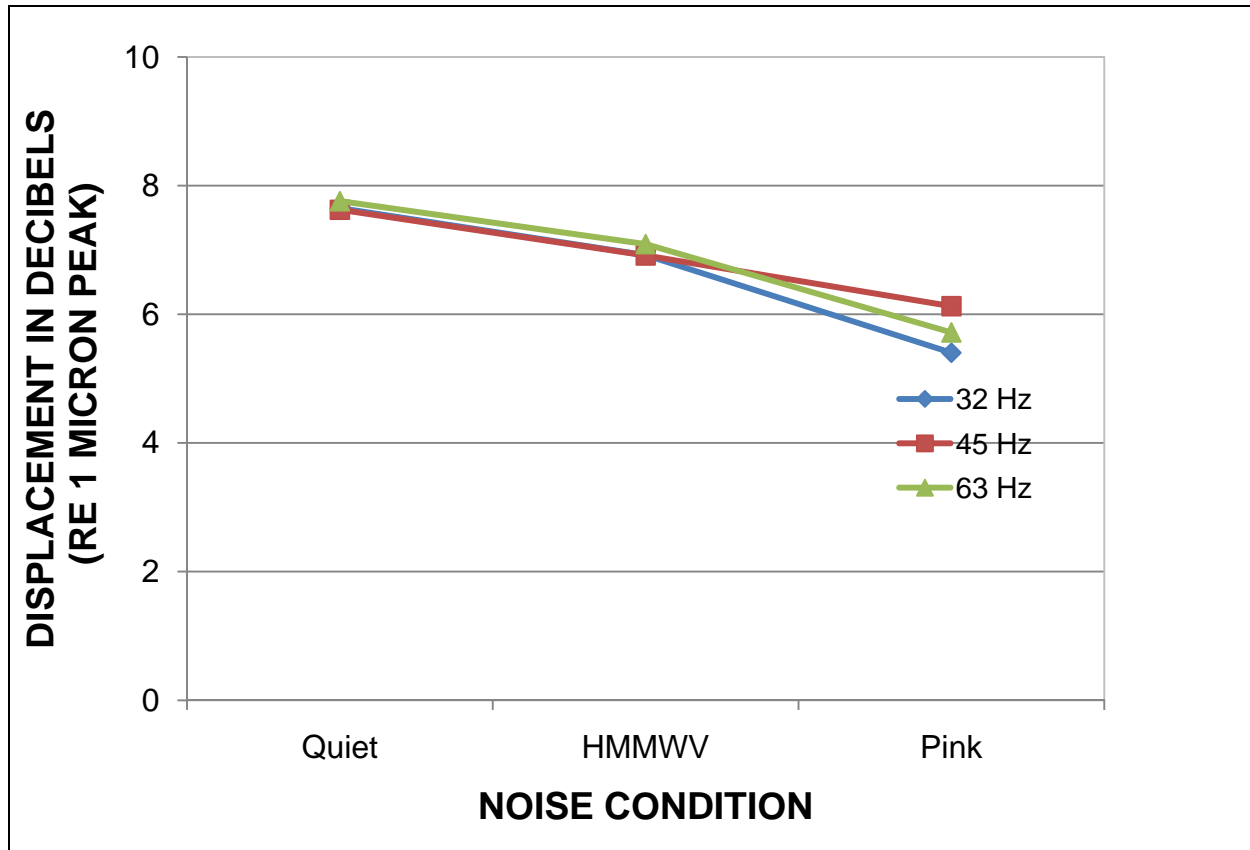


Figure 10. Noise condition \times frequency interaction for experiment 2.

3.2.1 Tactile Sensitivity by Head Region

Again, the data were organized into five head regions: central (C3, C4), frontal (FZ, F7), occipital (O1), parietal (P3, P4), and forehead (Fp2). Head location data were collapsed across frequency and noise condition. A repeated measures one-way ANOVA was used to evaluate vibration thresholds by head region, and the analysis revealed a significant main effect for head region, $F(4, 128) = 2.45, p = 0.05$.

In figure 11, the head regions are arranged from least to most sensitive to vibration stimulation and post hoc comparisons of the five head regions revealed that the forehead (Fp2) was significantly more sensitive to vibration than the central, frontal, and parietal regions of the head, $p < 0.05$. The occipital and forehead regions of the head demonstrated equal levels of sensitivity to vibration stimulation. Figure 12 shows displacement thresholds as a function of head region for experiments 1 and 2.

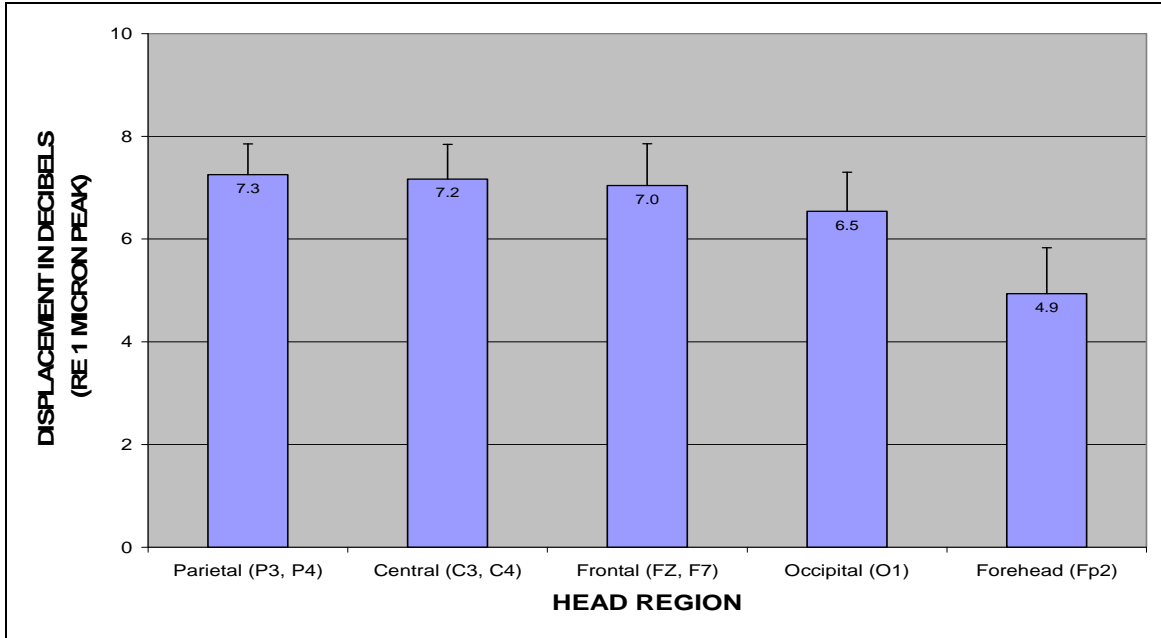


Figure 11. Mean displacement by head region for experiment 2. (The error bars indicate standard errors.)

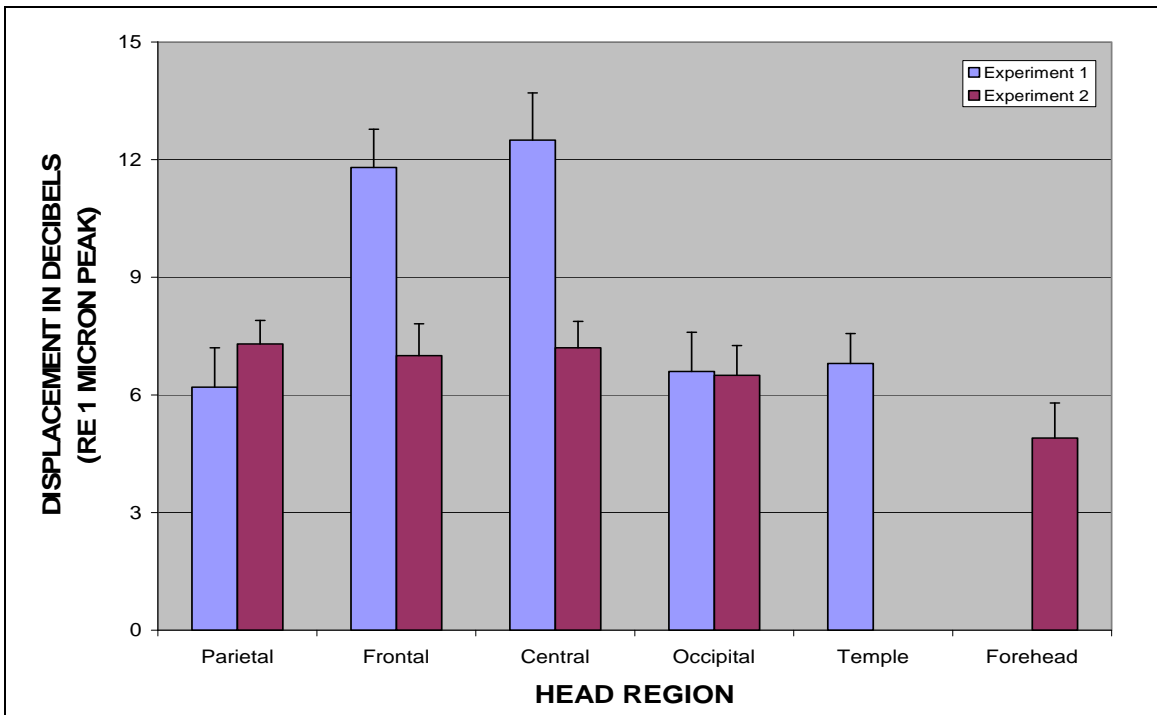


Figure 12. Mean displacement by head region for experiments 1 and 2. (The error bars indicate standard errors.)

3.2.2 Head Tactile Sensitivity Compared With Other Body Locations

Figure 13 presents displacement measured as a function of frequency for the head (from experiments 1 and 2) compared with tactile displacement for the abdomen, forearm, and fingertip. A relative comparison of the body sites shows that the head is more sensitive to vibration stimulation than the forearm and abdomen between 32–63 Hz. Also, the head is relatively equal to the fingertip in sensitivity to vibration stimulation at 32 Hz.

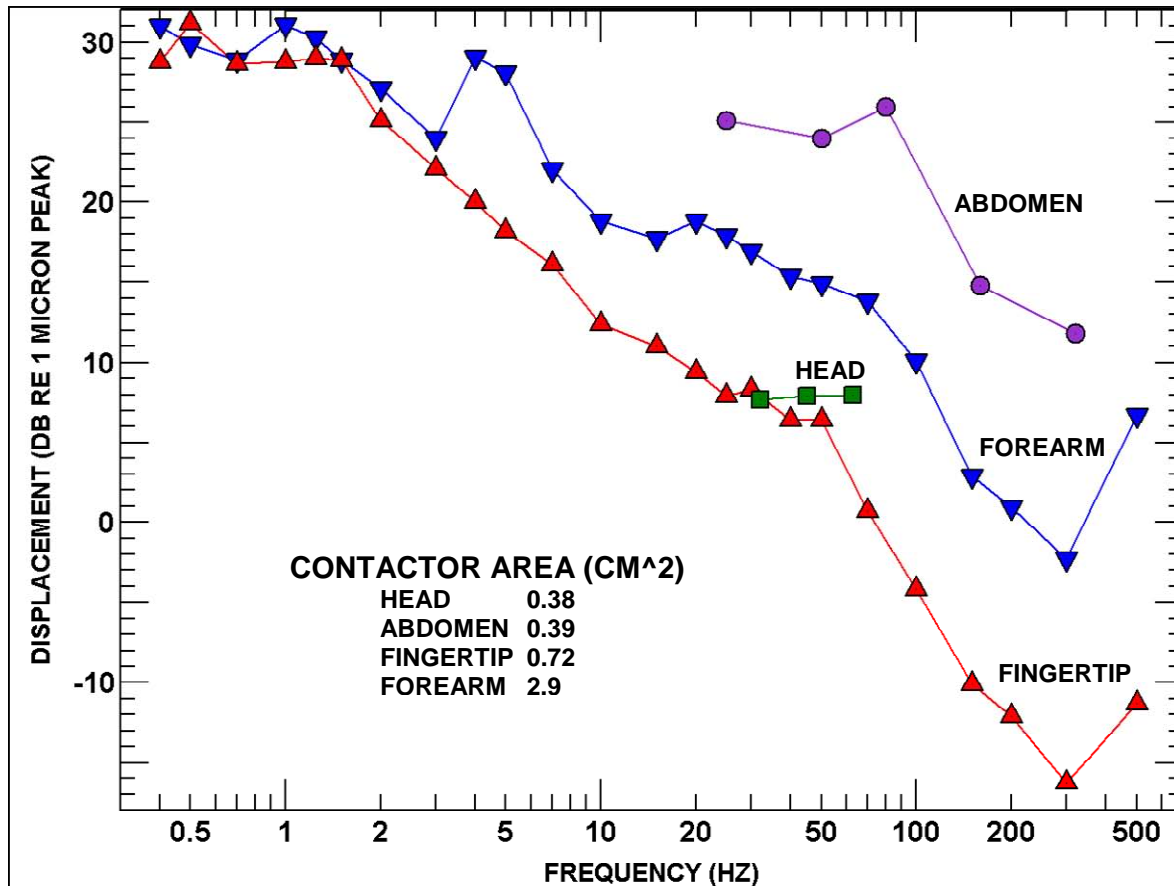


Figure 13. Vibratory stimulation threshold displacements measured on the head (mean of experiments 1 and 2) compared with other sites on the body. The area of the contactor that was used to measure threshold for each body site is given. (Adapted from Jones and Sarter [2008]).

4. General Discussion and Guidelines

4.1 Head Location

The data from experiments 1 and 2 provide a complete vibration sensitivity map of the head via head location positions in the 10-20 system of electrode placement. Vibration thresholds were measured for 15 of the 21 head locations in the system that represented all lobes of the cerebral

cortex. The most revealing information in the literature regarding the pattern of tactile sensitivity for the head was published by Weber (1834/1978), which suggests that the crown is less sensitive than the skin near the forehead, temples, and lower part of the back of the head. In Myles and Kalb (2009), the authors confirmed the general pattern of sensitivity for the scalp reported by Weber (1834/1978) using just seven head locations in the 10-20 system. In this study, using a more extensive array of head locations in the system, the authors again confirm Weber's (1834/1978) pattern of head sensitivity via the head region data.

In experiment 1, the parietal (PZ), occipital (O2), and temple (T3, T4) regions of the head were found to be most sensitive to vibration stimulation, and the central (CZ) and frontal (F3, F8) regions were found to be least sensitive to vibration stimulation. In experiment 2, the occipital (O1) and forehead (Fp2) regions of the head were found to be most sensitive to vibration stimulation, and the central (C3, C4), frontal (F7, FZ), and parietal regions (P3, P4) were found to be least sensitive to vibration stimulation. Because the parietal region of the head was not found to be highly sensitive in both experiments, it was eliminated as a viable region for use for head tactile communication. The authors conclude that the forehead, occipital, and temple regions are the most sensitive to vibration stimulation. Therefore, these regions of the head should be considered for purposes related to head tactile communication.

Based on the sensitivity data for the six head regions (forehead, occipital, temple, parietal, frontal, central) evaluated in this study, a four-tactor, circular head array is recommended for the design of an HMTD (see appendix). This design makes use of the most sensitive regions of the head and should be most intuitive for directional cueing and navigation applications. One tactile transducer should be placed in the middle of the forehead, one on each of the left and right temples, and one in the middle of the back of the head.

4.2 Frequency

4.2.1 Vibration Signals

Based on the results of a pilot test conducted in the beginning of this research program, the optimal frequency range for vibratory tactile signals used on the head is 32–64 Hz. It was reported that for frequencies above 64 Hz, both tactile and auditory perception of a signal could occur, but only tactile perception (no auditory perception) seems to occur for signals below 64 Hz (Myles and Kalb, 2009). This information is especially important for laboratory settings to ensure that tactile perception, not auditory perception, is truly being measured. As evidence, in most laboratory studies measuring vibration thresholds on the skin, participants don earphones, or background noise is used without earphones to mask the noise thought to be produced by a vibrating signal. The conveyance of vibration stimulation to the head/face is more susceptible to this phenomenon (than any other body site) because these locations are closer to the ear canal opening. Adherence to the optimal frequency range for vibration signals on the head will eliminate or significantly reduce sound transmission into the ear canal or cochlea from vibration signals.

4.2.2 Frequency and Sensory Receptors

Verrillo (1966) reported similar thresholds between 25–40 Hz for hairy skin. However, in experiment 2 the effect of frequency approached significance and may suggest that vibration thresholds were lower at 32 Hz than at 45 or 63 Hz. The thresholds used in the quiet environment in experiment 1 are re-reported from Myles and Kalb (2009) and exhibited the trend as well but were not produced in the HMMWV and pink noise environments. Even within the small range of 32–63 Hz, this finding may suggest that individuals are more sensitive to head vibration at lower frequencies.

Pacinian corpuscle (PC) receptors have a large receptive field, are excited by higher frequencies (>80 Hz), are numerous in distal joints, and are located in deep tissues of the skin (Mahns et al., 2006; Sherrick and Cholewiak, 1986; Sherrick et al., 1990). Non-PC receptors have a small receptive field, are excited by lower frequencies (<80 Hz), and are located in superficial skin (Mahns et al., 2006; Sherrick et al., 1990). According to Mahns et al. (2006), the detection of vibration stimulation in hairy skin is dependent upon sensory fibers found in hair follicles called hair follicle afferent (HFA) fibers (populous in non-PC receptors) as opposed to rapidly adapting (RA) fibers (populous in PC receptors) found in glabrous (i.e., non-hairy) skin.

The characteristic makeup of the head or scalp, which is populated with HFA fibers, may help to explain why the head might be more sensitive to vibration stimulation at 32 Hz. A body site that is heavily populated with HFA fibers is more likely to respond to vibration stimulation at the lower frequencies; one would imagine this would enhance perception at the lowest frequency within a given range. The authors are not asserting that the head will exhibit an optimal response to vibration at perhaps 5 Hz because that particular frequency was not part of the scope of this project and would need to be investigated further. Also, the head, unlike other body sites such as the forearm, is not surrounded by distal joints that contain RA fibers that respond to vibration stimulation at the higher frequencies. Vibration seldom stimulates one fiber/receptor but moves throughout nearby skin tissues (Sherrick and Cholewiak, 1986; van Erp and van den Dobbelen, 1998) that can excite fibers that respond to both the lower and higher vibration frequencies. This is seen in figure 13, where the hairy forearm and abdomen exhibit similar sensitivity thresholds (often seen for non-hairy skin) that begin to decrease at ~100 Hz with maximum sensitivity occurring between 250–300 Hz (Bolanowski et al., 1988; Lamofe and Keemink, 1988; Verrillo, 1962, 1966) where the trend for the head should begin to show an increase in thresholds at 100 Hz. For hairy skin to show similar sensitivity trends like that of non-hairy skin, vibration on the forearm and abdomen recruit nearby RA fibers at the higher frequencies. Because the head/scalp has much more moderate access to RA fibers, the authors speculate that increasing thresholds are likely to be seen at 100 Hz.

No general statements can be made regarding vibration sensitivity for frequencies lower than 32 Hz, but of the frequency range used in this study, 32 Hz appears to be the reasonable frequency choice for the optimal perception of vibration on the head.

4.2.3 Frequency of the Signal and User Discomfort

For tactile communication on the head, vibration signals also need to be evaluated for user comfort. This characteristic is demonstrated from the user's perspective (Brill and Gilson, 2006; Hawes and Kumagai, 2005; Redden et al., 2007). Hawes and Kumagai (2005) reported a preference for a chest tactile system vs. a head tactile system because participants thought the head tactile system applied too much energy to the head, causing them discomfort and headaches. Brill and Gilson (2006) also reported user aversion to a head tactile system for similar reasons such as dizziness, disorientation, and a general feeling of unsettledness. While Brill and Gilson (2006) did not report the frequency of their signal, Hawes and Kumagai (2005) reported that they used a 260-Hz signal for both the chest and head displays. The authors agree with the perspectives of the user because during the pilot test, vibration signals in the 5- to 300-Hz range were created and tested. It was discovered that above 150 Hz, user discomfort becomes a serious issue, and these frequencies should not be used for vibrating the head. During debriefing in Myles and Kalb (2009) and in this study, no participants reported discomfort or pain due to the vibration signals.

4.3 Background Noise

Noise condition by frequency interactions suggests that at 32 Hz the type of background noise may increase one's sensitivity to vibration stimulation on the head. Specifically, in the quiet condition in experiment 1, thresholds were lowest at 32 Hz, and in the pink condition in experiment 2, thresholds were lowest at 32 Hz. Because each noise by frequency interaction was not found in both experiments, a repeat study using the current methodology (or at least the quiet and pink noise condition levels) is advocated before general recommendations are made regarding the effect of background noise on head tactile sensitivity. For both experiments, tactile sensitivity in the HMMWV condition was not affected by frequency. This finding is promising for real-world applications of Soldier performance on the battlefield because it shows the potential to detect tactile signals on the head regardless of exposure to HMMWV noise in the background.

4.4 Head Tactile Communication and Bone Conduction

The issue concerning whether individuals perceive vibration signals through auditory or tactile perception is critical to the design of an HMTD. Since the tactile display will be head-mounted, most would agree that the logical placement for the tactile transducers would be on the helmet. However, with so many other systems mounted to the helmet, designing the HMTD as part of an existing system would be most beneficial to the Soldier in that the Soldier would benefit from novel technology that would help to alleviate overload on the visual and auditory channels, with very little additional equipment and weight to carry. Distinguishing between tactile vs. auditory perception as a function of frequency is important if the HMTD will be integrated with existing bone conduction (BC) systems to improve Soldier performance. The three important parameters

to consider for integrating the two systems are type of transducer, head location placement, and frequency of the stimuli. The tactile and BC transducers share similar properties, and the chosen transducer must offer characteristics where both speech and tactile signals are conveyed. Either the same BC transducers could be used for both speech or tactile communications on a time-sharing basis or a system of two independent transducers could perform these functions. Additional research is needed to make an informed recommendation regarding the dual use of tactile or BC transducer equipment for both tactile and BC communication. According to McBride et al. (2005), the vertex (CZ) and the temples (T3, T4) are head locations that are most suitable for BC vibrator placement. Based on the results from this study, the temples (T3, T4) are also suitable head locations for vibration stimulation or head tactile communication.

5. Conclusions

Eriksson et al. (2008) reported Soldier preference for a directional cueing tactile display over similar visual and auditory displays. Dorneich et al. (2006) found that a tactile cueing system mitigated the cognitive challenges associated with navigation in an unfamiliar environment. Elliott et al. (2006) demonstrated that tactile vs. compass and GPS navigation allowed greater accuracy for reaching waypoints, and tactile vs. compass navigation facilitated faster navigation and walking speeds. Savick et al. (2008) reported a lower response time and lower ratings for frustration and effort with the use of a tactile vs. visual and auditory displays for target acquisition and robot navigation tasks. These tactile applications have been used successfully on the torso, and the authors envision success conveying similar information via the head. Therefore, the guidelines for head tactile communication summarized in this report will be influential in the design of an HMTD to support a directional cueing or covert communication system for Soldiers. Guidelines and recommendations for HMTDs are listed as follows:

1. The forehead, occipital, and temple regions of the head are most sensitive to vibration stimulation. Therefore, these regions should be considered for purposes related to head tactile communication.
2. A four-tactor, circular head array is recommended for an HMTD design (see appendix).
3. The reasonable frequency for the optimal perception of vibration on the head appears to be 32 Hz.
4. Above 150 Hz, user discomfort becomes a serious issue; these frequencies should not be used for vibrating the head.
5. The vertex (CZ) and the temples (T3, T4) are head locations that are most suitable for BC vibrator placement. The temples (T3, T4) are also suitable head locations for vibration stimulation or head tactile communication.

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**Appendix. Diagram of the Proposed HMTD: Four-Tactor,
Circular Head Array**

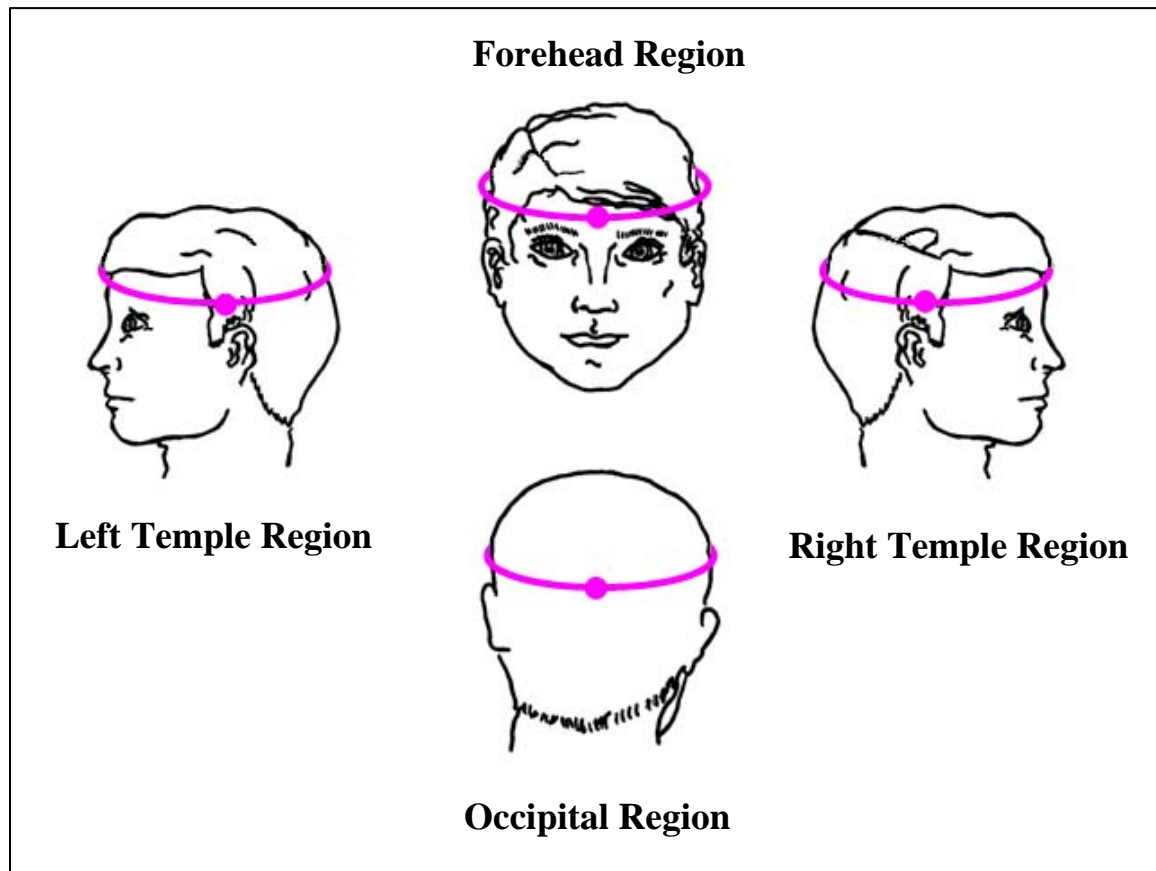


Figure A-1. Diagram of the proposed HMTD: four-tactor, circular head array.

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